

# NEUTRINO MASS FROM THE LYMAN-ALPHA FOREST

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The quest for the neutrino mass is a central goal in contemporary cosmology, subject to intense scrutiny, and among different large-scale structure tracers the Lyman- $\alpha$  forest is re-emerging as a unique tool to probe the neutrino mass at high-redshift – through characteristic imprints on the transmitted Lyman- $\alpha$  flux. A detailed modeling of the low-density regions of the intergalactic medium in presence of massive neutrinos on scale ranging from a few to hundreds of megaparsecs is required, if one wants to interpret state-of-the-art data from observations of quasar spectra. To this end, we provide a suite of hydrodynamical simulations made with Gadget-3, spanning different volumes and having a range of resolutions and neutrino masses (from  $M_\nu = 0.1$  to  $0.8$  eV, assuming 3 degenerate species), specifically designed to meet the requirements of the Baryon Acoustic Spectroscopic Survey (BOSS). We adopted a particle-type implementation of massive neutrinos, and chose cosmological parameters compatible with the latest Planck (2013) results. While the resolution requirements match the quality of the SDSS-III/BOSS data, our numerical simulations will also establish a useful theoretical ground for upcoming surveys such as SDSS-IV/eBOSS and DESI. In the very near future, data from leading spectroscopic surveys will allow measuring the absolute mass scale of neutrinos, and determining the exact nature of the neutrino mass hierarchy; hence, we expect that this modeling will become increasingly useful.

## 1 Massive Neutrinos and Structure Formation

At the interface between particle physics and cosmology, neutrino science has received renewed interest recently, after the breakthrough discovery over the last decade that neutrinos are massive. Hence, massive neutrinos should be included in the concordance  $\Lambda$ CDM model dominated by a dark energy (DE) component, which in general only assumes a minimal neutrino mass of  $0.06$  eV. While neutrino oscillation experiments are sensitive only to differences in the squares of neutrino masses, cosmology offers a unique ‘laboratory’ with the best sensitivity to the neutrino mass: primordial neutrinos leave their imprint into several large-scale structure (LSS) observables, and because of free-streaming they significantly alter structure formation. Therefore, cosmology can place competitive limits on the neutrino mass scale and hierarchy.

Neutrinos must be considered as extra radiation while ultra-relativistic, but once non-relativistic they behave as an additional cold dark matter (CDM) component and participate in structure formation on scales greater than their free-streaming scale: the overall result is a suppression of power on small scales, and a delay in matter domination (Lesgourgues & Pastor 2006). Neutrinos in the mass range  $0.05 \text{ eV} \leq m_\nu \leq 1.5 \text{ eV}$  become non-relativistic in the redshift interval  $3000 \geq z \geq 100$ , approximately around  $z_{\text{nr}} \simeq 2000(m_\nu/1\text{eV})$ . While the effect of cosmological neutrinos on the evolution of density perturbations in the linear regime is well-understood, less is known in the nonlinear regime: this fact motivates the present study.

Massive neutrinos can be studied through their impact on the CMB, particularly in the

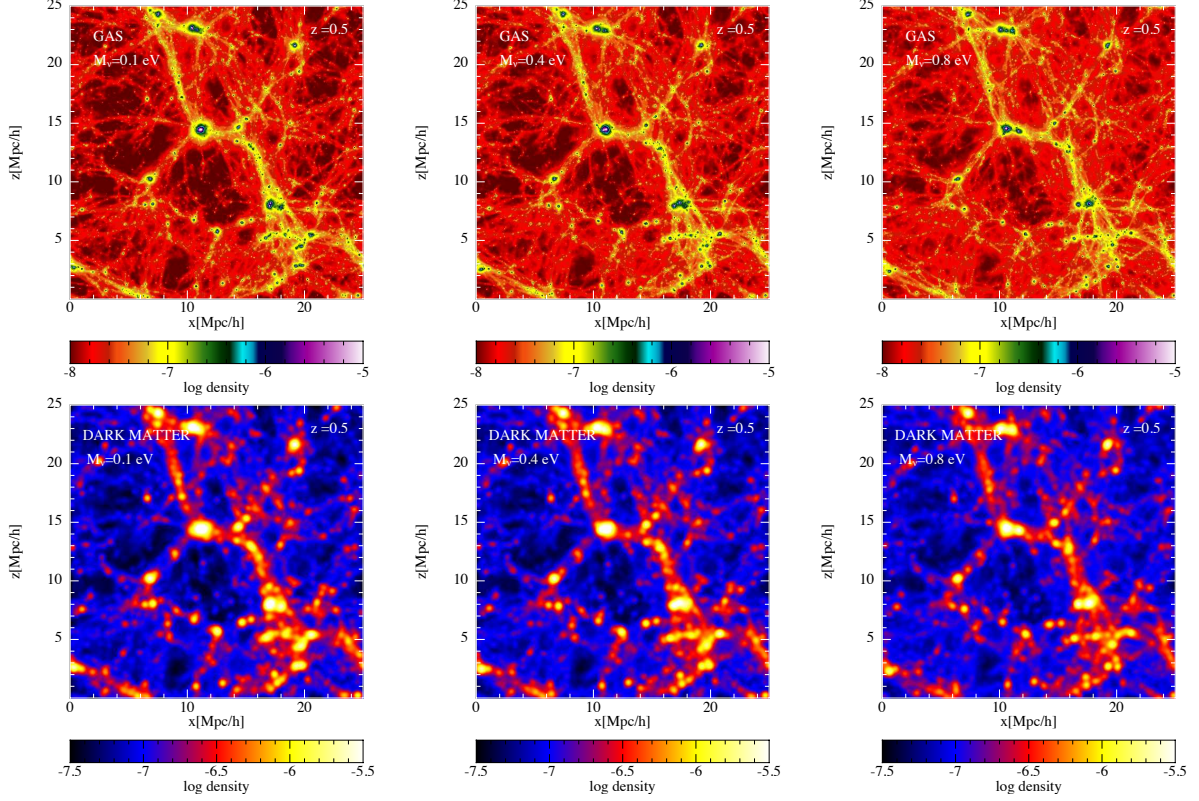


Figure 1: Examples of snapshots of the gas (top panels) and dark matter (bottom panels) components at  $z = 0.5$ , from simulations with  $25 h^{-1} \text{Mpc}$  box size and resolution  $N_p = 192^3$  particles/type. The panels are full projections of the density field in the  $x$  and  $z$  directions across  $y$  and smoothed with a cubic spline kernel, obtained from simulations having a total neutrino mass  $M_\nu = 0.1 \text{ eV}$  (left),  $M_\nu = 0.4 \text{ eV}$  (middle), and  $M_\nu = 0.8 \text{ eV}$  (right).

polarization maps, and by using several baryonic tracers of the LSS clustering of matter such as the 3D power spectrum from galaxy surveys, the Sunyaev-Zel'dovich effect in galaxy clusters, cosmic shear through weak lensing, or the Lyman- $\alpha$  (Ly $\alpha$ ) forest. The latter observable has generally received less attention in the literature, but is currently emerging as a promising window into the high-redshift Universe, being at a redshift range inaccessible to other LSS probes and spanning a wide interval in redshift. In particular, the suppression of growth of cosmological structures on scales smaller than the neutrino free-streaming distance makes the Ly $\alpha$  forest a good tracer of the neutrino mass, and measurements of the mean Ly $\alpha$  transmission flux and its evolution allow constraining the basic cosmological parameters with improved sensitivity.

At the present time, the best Ly $\alpha$  forest data and the most precise measurement of the Ly $\alpha$  flux power spectrum come from the Baryon Acoustic Spectroscopic Survey (BOSS) – see Dawson et al. (2013), and Palanque-Delabrouille et al. (2013). In order to interpret the information contained in this remarkable data set and control the systematics involved, numerical simulations at equivalent or superior precision of this survey are required, particularly at lower redshifts and smaller scales ( $1\text{--}40 h^{-1} \text{Mpc}$ ) where for massive neutrinos the nonlinear evolution of density fluctuations becomes significant. Despite their intrinsic limitations and uncertainties, simulations allow one to self-consistently model the interplay between gravity and gas pressure on the structure of the photoionized intergalactic medium (IGM), so that most of the observed properties of the Ly $\alpha$  forest are reproduced, and to gain a better understanding of the role and effects of massive neutrinos in the complex process of structure formation – as we discuss next.

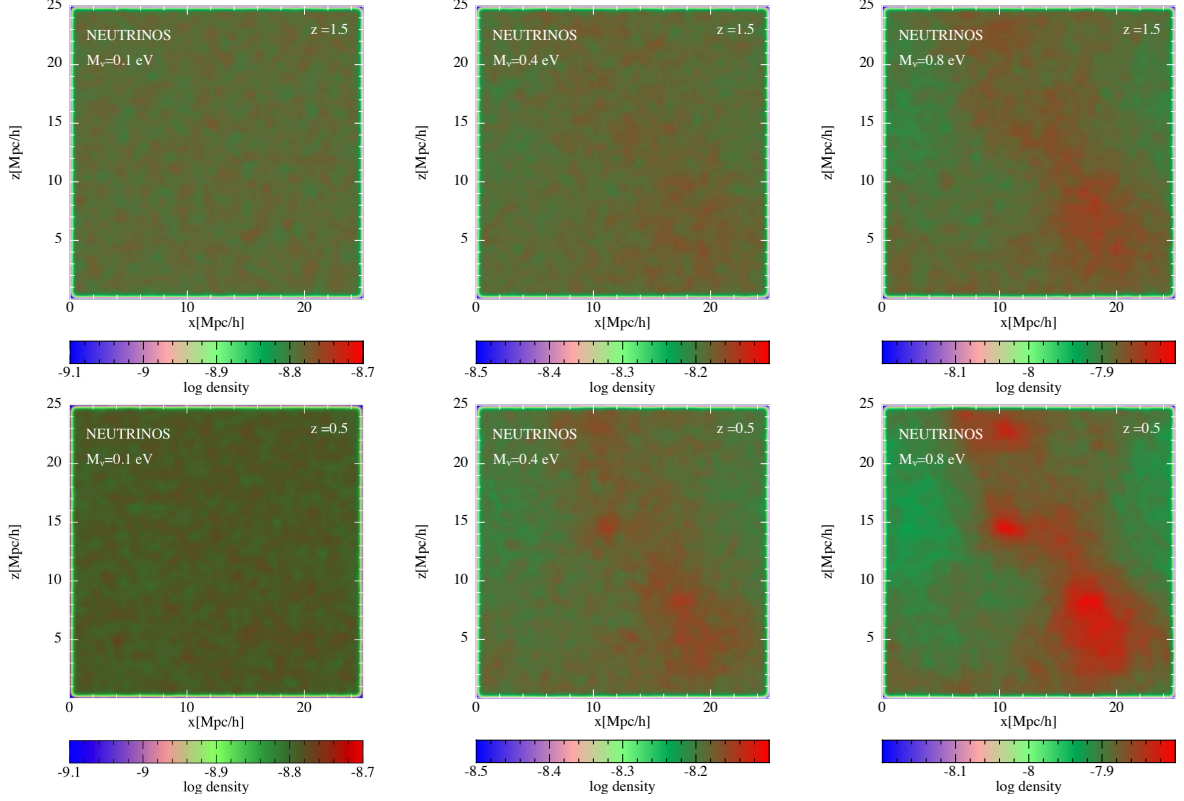


Figure 2: Density evolution of the neutrino component at  $z = 1.5$  (top panels) and  $z = 0.5$  (bottom panels), from simulations with  $25 h^{-1}\text{Mpc}$  box size and resolution  $N_p = 192^3/\text{type}$ . The total neutrino mass increases from left to right, being  $M_\nu = 0.1$  eV (left),  $M_\nu = 0.4$  eV (central), and  $M_\nu = 0.8$  eV (right). The distribution of the neutrino density has been smoothed with a cubic spline kernel to eliminate spurious Poisson noise at small scales.

## 2 Suite of Hydrodynamical Simulations with Massive Neutrinos

We have produced a suite of 48 cosmological hydrodynamical simulations with CDM, baryons, and either a varying neutrino mass and fixed cosmological and astrophysical parameters, or with a fixed neutrino mass and slight variations in the basic cosmological and astrophysical parameters around what we termed the ‘best-guess’ – namely, the reference simulation set with Planck (2013) cosmological parameters and a massless neutrino component. Box sizes and resolutions range from  $25 h^{-1}\text{Mpc}$  to  $100 h^{-1}\text{Mpc}$ , and from  $N_p = 192^3$  to  $N_p = 768^3$  particles/type, respectively. Visual examples of the density distribution of the gas and dark matter components at  $z = 0.5$  in cosmologies with massive neutrinos are shown in Figure 1. Extensive details on the numerical aspects of these simulations, and on the implementation of massive neutrinos, can be found in Rossi et al. (2014). In particular, along the lines of Viel et al. (2010), we have modeled neutrinos as an additional type of particle in the  $N$ -body setup, and carried out a full hydrodynamical treatment well-inside the nonlinear regime, without making any approximations for the evolution of the neutrino component. We have considered 3 degenerate species of massive neutrinos implemented as a single particle-type, with total mass  $M_\nu = 0.1, 0.2, 0.3, 0.4, 0.8$  eV. Figure 2 is a visual example of the density evolution of the neutrino component for different  $M_\nu$  ranges, at  $z = 1.5$  (top panels) and  $z = 0.5$  (bottom panels). Simulations were made with Gadget-3 (Springel 2005), CAMB (Lewis, Challinor & Lasenby 2000), and 2LPT (Crocce et al. 2006) initial conditions starting at  $z = 30$ , and contain improvements at all levels with respect to previous work. We stored snapshots at redshifts between  $z = 4.6$  and  $z = 2.2$  in  $\Delta z = 0.2$  intervals, and for each simulation we extracted 100,000 random pencil beam lines of sight (LOS).

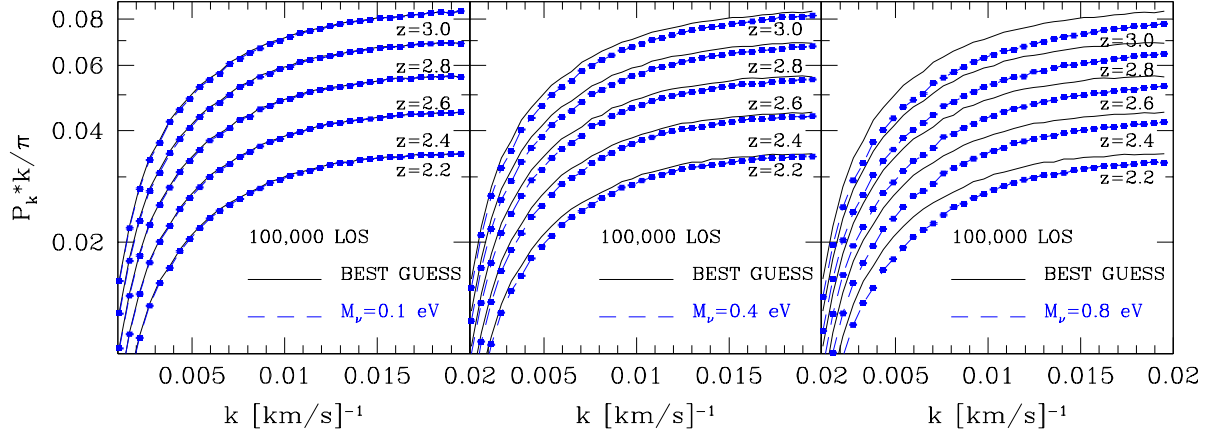


Figure 3: One-dimensional flux power spectra computed from the suite of simulations described in the main text, for different values of the neutrino mass (dashed lines and points) as specified in the panels, averaged over 100,000 LOS at different  $z$ -intervals. Black lines are the corresponding measurements obtained from the ‘best-guess’, which contains only a massless neutrino component. Results are obtained by applying the splicing technique.

### 3 Results, Applications, and Future Prospects

The free-streaming of neutrinos causes a suppression of the power spectrum of the total matter distribution at scales probed by the Ly $\alpha$  forest data, which is larger than the linear theory prediction by about  $\sim 5\%$  at scales  $k \sim 1 \, h\text{Mpc}^{-1}$  when  $M_\nu = 0.4 \, \text{eV}$ , and is strongly redshift dependent. This effect propagates into the 1D flux power spectrum, and affects the statistical properties of the Ly $\alpha$  transmitted flux fraction. Figure 3 shows examples of 1D flux power spectra across several redshift slices, and for a varying total neutrino mass – i.e.  $M_\nu = 0.1 \, \text{eV}$  (left),  $M_\nu = 0.4 \, \text{eV}$  (center),  $M_\nu = 0.8 \, \text{eV}$  (right). Results are averaged over 100,000 LOS at different  $z$ , as indicated in the panels, and are obtained with the splicing technique introduced by McDonald (2003) and extensively tested in Borde et al. (2014). This allows us to achieve an equivalent resolution of  $3 \times 3072^3 \simeq 87$  billion particles in a  $(100 \, h^{-1}\text{Mpc})^3$  box size with a 2% global error across the full  $k$ -range of interest – which is at the same level of the current uncertainties in available observational data – without the need of running a single but computationally prohibitive numerical simulation. The flux power spectrum is sensitive to a wide range of cosmological and astrophysical parameters and instrumental effects; it can be used as a probe of the primordial matter power spectrum on scales of  $0.5 - 40 \, h^{-1}\text{Mpc}$  at  $2 \leq z \leq 4$ , and to determine cosmological parameters, the nature of dark matter through its shape and redshift dependence, and the neutrino mass.

We are currently combining results of these simulations with Ly $\alpha$  forest data from BOSS, in order to constrain cosmological parameters and the neutrino mass with improved sensitivity, and fully exploit the orthogonality of the Ly $\alpha$  forest with other LSS probes. Our simulations and techniques can also be useful for upcoming surveys such as SDSS-IV/eBOSS (Comparat et al. 2013) and DESI (Schlegel et al. 2011), which will eventually lead to the determination of the absolute mass scale and hierarchy of neutrinos in the very near future.

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